# I.    INTRODUCTION

National parks in the Rocky Mountains and northern Great Plains include lands of exceptional ecological and cultural significance.  The National Park Service (NPS) maintains the world's most admired and imitated system of parks.  Millions of visitors each year are attracted by the outstanding scenery and the unspoiled nature of park ecosystems.  However, the ecological integrity of these ecosystems is threatened by increasing demands on park usage and pollutant emissions outside park boundaries.  Air quality is fundamentally important to the preservation of healthy ecosystems.  Most of the parks in the Rocky Mountains and northern Great Plains receive generally low levels of atmospheric pollutants (Sisterson et al. 1990, Smith 1990).  Nevertheless, sensitive aquatic and terrestrial ecosystems, especially those at high elevations, can potentially be degraded by existing or future pollution (Peterson et al. 1992).  Elevated emission levels of sulfur dioxide ($SO_2$) and nitrogen oxides and elevated concentrations of ozone ($O_3$) have been measured in some portions of these regions (Sisterson et al. 1990).  Some areas also have impaired visibility.

Recognizing the valuable role that scientific research can play in proper management of a park, the NPS Director commissioned the National Research Council to review the Agency's research program.  The review committee (National Research Council 1992) concluded that there was an urgent need to accelerate research in the parks to:

·    inventory the natural resources in order to protect and manage the resources and detect changes;

·    better understand the natural ecosystems in the parks; and

·    assess specific threats to the parks.

In accordance with these recommendations, the Air Resources Division (ARD) of the NPS initiated a series of projects to assess air quality in selected parks.  The subject of this report is one such project, which is designed to take a proactive position in assessing potential threats from air pollution to national parks in the Rocky Mountains and northern Great Plains.

To maintain healthy ecosystems and protect visibility, it is imperative that land managers monitor and assess levels of atmospheric pollutants and ecological effects in the national parks. Knowledge of emissions inventories, coupled with scientific understanding of the effects of pollutants on natural resources, will provide land managers with a framework within which to protect sensitive resources within the parks from degradation due to atmospheric pollutants.

The Clean Air Act and the NPS Organic Act provide mandates for protecting air resources in NPS areas.  In Section 160 of the Clean Air Act, Congress states that one of the purposes of the Act is to "preserve, protect and enhance the air quality in national parks, national wilderness areas, national monuments, national seashores and other areas of special national or regional natural, recreation, scenic, or historic value."  According to the Clean Air Act and subsequent amendments, Federal land managers have "...an affirmative responsibility to protect the air quality related values (AQRVs)...within a Class I area."  AQRVs include flora, fauna, bodies of water and other resources that may be potentially damaged by air pollution.  A Class I designation allows only small increments of pollution above already existing levels within the area.  National Parks over 6,000 acres and national wilderness areas over 5,000 acres, that were in existence before August of 1977, are designated as Class I areas.  All other areas managed by the NPS are designated Class II and a

greater amount of air quality degradation is allowed by the Clean Air Act.

The NPS Class I areas within the Rocky Mountains (Colorado, Montana, and Wyoming) include (alphabetically) Glacier National Park (GLAC), Grand Teton National Park (GRTE), Rocky Mountain National Park (ROMO), and Yellowstone National Park (YELL).  NPS Class I areas within the northern Great Plains (North Dakota and South Dakota) include Badlands National Park (BADL), Theodore Roosevelt National Park (THRO), and Wind Cave National Park (WICA).

## A.    OBJECTIVES

The principal goal of this report is to evaluate the status of air quality and air pollution effects and to identify information needs for air quality related issues in NPS Class I areas in the Rocky Mountains and northern Great Plains.  To support the mandate to protect AQRVs in Class I areas, the following specific objectives have been identified for the report:

- ·    provide updated summaries of monitoring data on visibility and on pollutant concentrations and deposition, both temporally (hourly, seasonally, annually) and spatially (regional, statewide, park);

- ·    conduct comprehensive analyses of documented and potential ecological effects of various atmospheric pollutants and exposures (chronic, episodic) on terrestrial and aquatic systems;

- ·    compile inventories of pollution-sensitive components or receptors of ecosystems, and the critical or target loading of pollutants that would be likely to cause changes in the sensitive receptors;

- ·    assess key knowledge deficits and additional information required to adequately protect resources sensitive to potential degradation by poor air quality.

The report addresses these objectives by providing a summary of current and historical monitoring data for pollutants, a synthesis of knowledge on the ecological effects of atmospheric pollutants, and a park-specific assessment of pollution vulnerability.

## B.    SCOPE AND ORGANIZATION

This report is based on a concern for the ecological integrity of Class I areas.  Thus, the scope is limited to addressing potential threats to:  (1) terrestrial resources (primarily from nitrogen (N) and sulfur (S) deposition [including gaseous forms], and ozone exposure), (2) aquatic resources (primarily from N and S deposition), and (3) visibility (primarily from particulates and aerosols). Exposure to trace metals, fluoride, and hydrogen sulfide is covered in less detail, and radionuclides and organic toxins are not addressed.  With regard to trace metals, an extensive analysis of the topic is not justified, because at present the problem is localized in proximity to industrial smelters.  Also, information is lacking with which to evaluate the dispersal of trace metals in the Rocky Mountain and northern Great Plains regions via airborne particles.

Although the report attempts to address many of the critical issues facing each park, partial coverage of some topics should not be interpreted as a judgment that these topics are not important or relevant to the issue of air pollution effects.  For example, little mention is made of the direct effect of pollutants on fish or other important taxonomic groups.  These omissions often reflect the lack of information on these topics rather than any reflection on their ecological significance.

It is hoped that this report will serve audiences including staff with the NPS Air Resources Division, regional air quality officers, individual park staff and organizations dealing with air quality issues in the Rocky Mountain and northern Great Plains regions.  The report is structured to present relevant information on regional issues and then to discuss individual NPS Class I areas.

It should be noted that some aspects of measuring air pollution and air pollution effects are evolving and scientists remain divided with respect to appropriate assessment techniques.  We have not attempted to resolve these issues in this report but have simply identified acceptable monitoring strategies.

## C.      BACKGROUND

### 1.      Deposition

There are relatively few data on air quality in the Rocky Mountain and northern Great Plains regions, with most data being short-term and/or from urban areas remote from wildland locations.  General patterns of N and S deposition can be inferred from national databases, but ozone distribution is more difficult to estimate.  It is known that air pollution in urban areas adjacent to the Rockies, especially at locations east of the Front Range in Colorado, has increased considerably during the last 30 to 40 years.  Dispersion and transport of pollutants vary locally, but there are clearly periods of high ozone exposure every summer.  The challenge is to quantify the spatial distribution of this exposure from the limited database.  Establishment of a current reference point for air quality, in combination with additional monitoring, is needed to detect long-term trends.

The estimation of deposition of atmospheric pollutants in high-elevation areas in the western United States is especially difficult because all components of the deposition (rain, snow, cloudwater, dryfall and gases) have seldom been measured concurrently.  Even measurement of wet deposition remains a problem because of the logistical difficulties in operating a site at high elevation.  Portions of the wetfall have been measured by using snow cores (or snow pits), bulk deposition, and automated sampling devices such as those used at the National Atmospheric Deposition  Program/ National Trends Network (NADP/NTN) sites. All of these approaches suffer from limitations that cause problems with respect to developing annual deposition estimates.  The snow sampling includes results for only a portion of the year and may seriously underestimate the load for that period if there is a major rain-on-snow event.  Bulk deposition samplers are subject to contamination problems from birds and litterfall.

Weekly data on dry deposition are available at four sites in the Rocky Mountain region, collected within the Clean Air Status and Trends Network (CASTNet).  The sites are located at Gothic, CO; Pinedale and Centennial, WY; and Glacier NP, MT.  Sites have also been installed in ROMO and YELL, but data from these sites are not yet available.  The CASTNet file contains weekly atmospheric concentration (from filter pack samplers), deposition velocity, and estimated weekly dry deposition fluxes of S and N.  Dry deposition estimates were extremely low at all sites, well under 0.5 kg/ha/yr for each constituent.  Based on these data, the general scarcity of significant point sources in close proximity to the parks, and the generally low levels of measured wet deposition, we conclude that dry deposition of S and N at parks considered in this report is low to negligible.

The need to measure or estimate cloudwater, dryfall and gaseous deposition complicates the difficult task of measuring and monitoring total deposition.  Cloudwater can be an important portion of the hydrologic budget in high elevation forests (Harr 1982), and failure to capture this portion of the deposition input could lead to substantial underestimation of annual deposition.  Furthermore, cloudwater chemistry has the potential to be more acidic than rainfall.  Dryfall from wind-borne soil can constitute major input to the annual deposition load, particularly in arid environments.  Aeolian inputs from dryfall can provide a major source of acid neutralization not generally measured in other forms of deposition.  Gaseous deposition is calculated from the product of ambient air concentrations and estimated deposition velocities.  The derivation of deposition velocities is subject to considerable debate.  In brief, there is great uncertainty regarding the amount of current deposition of atmospheric pollutants in the Class I areas and throughout many of the mountainous regions of the western United States.

## 2.     Air Quality Regulations

Criteria pollutants are those pollutants for which the U.S. Environmental Protection Agency (EPA) has established National Ambient Air Quality Standards (NAAQS) as directed by the Clean Air Act (Table I-1).  Standards were established for the pollutants that are emitted in significant quantities throughout the country and that may be a danger to public health and welfare.  The primary NAAQS is designed to protect human health while the secondary NAAQS is designed to protect the public welfare from the adverse effects of the pollutant.  The Clean Air Act defines public

| Constituents | Averaging Time | Primary Standard | Secondary Standard |
|---|---|---|---|
| | Annual Arith. Mean | 30 ppbv | none |
| Sulfur Dioxide | 24-hour[a] | 140 ppbv | none |

Table I-1.  National Ambient Air Quality Standards.

| | 3-hour[a] | none | 500 ppbv |
|---|---|---|---|
| PM-10 | Annual Arith. Mean[b] | 50 $\mu g/m^3$ | same |
| | 24-hour[b] | 150 $\mu g/m^3$ | same |
| PM-2.5 | Annual[b] | 15 $\mu g/m^3$ | same |
| | 24-hour[b] | 65 $\mu g/m^3$ | same |
| Carbon Monoxide | 8-hour[a] | 9,000 ppbv | same |
| | 1-hour[a] | 35,000 ppbv | same |
| Ozone | 8-hour[c] | 80 ppbv | same |
| Nitrogen Dioxide | Annual Arith. Mean | 50 ppbv | same |
| Lead | Calendar Quarter | 1.5 $\mu g/m^3$ | same |

[a] Concentration is not to be exceeded more than once per calendar year.
[b] Compliance is based on concentrations averaged over a 3-year period.
[c] Compliance is based on a 3-year average of the annual fourth-highest daily maximum 8-hour concentration.

welfare effects to include, but not be limited to, "effects on soils, water, crops, vegetation, manmade materials, animals, wildlife, weather, visibility and climate, damage to and deterioration of property, and hazards to transportation, as well as effects on economic values and on personal comfort and well-being". The standards are defined in terms of deposition-averaging times, such as annual or hourly, depending on the type of exposure associated with health and welfare effects. For some pollutants, there are both short-term and long-term standards. Criteria pollutants include ozone ($O_3$), carbon monoxide (CO), nitrogen dioxide ($NO_2$), sulfur dioxide ($SO_2$), particulate matter less than 10 $\mu$m (PM-10), particulate matter less than 2.5 $\mu$m (PM-2.5) and lead (Pb). Baseline data on criteria pollutants collected by a national monitoring system are used to determine if the NAAQS are met and to track pollutant trends.

Air quality within Class I lands of the NPS system is subject to the "prevention of significant deterioration (PSD)" provisions of the Clean Air Act. The primary objective of the PSD provisions is to prevent substantial degradation of air quality in areas that comply with NAAQS, and yet maintain a margin for industrial growth. A PSD permit from the appropriate air regulatory agency is required to construct a new pollution source or modify an existing source (Bunyak 1993). A permit application must demonstrate that the proposed polluting facility will (1) not violate national or state ambient air quality standards, (2) use the best available control technology to limit emissions, (3) not violate either Class I or Class II PSD increments for $SO_2$, $NO_2$, and particulate matter (Table I-2), and (4) not cause or contribute to adverse impacts to AQRVs in any Class I area (Peterson et al. 1992).

The PSD increments are allowable pollutant concentrations that can be added to baseline concentrations. The values chosen as PSD increments by Congress were not selected on the basis of concentration limits causing impacts to specific resources. Therefore, it is possible that pollution increases exceeding the legal Class I increments may not cause damage to Class I areas. It is also possible that resources in a Class I area could be affected by pollutant concentrations that do not exceed the increments. The role of the Federal land manager is to determine if there is potential for additional air pollution to cause damage to sensitive receptors whether or not the PSD increments have been exceeded. Even if a proposed facility is not expected to violate Class I increments, the Federal land manager can still recommend denial for a permit by demonstrating that there will be adverse impacts in the Class I area. Provisions for mitigation can be recommended by the Federal land manager to the agency that issues permits.

The following questions must be answered for PSD permit applications:

- What are the identified sensitive AQRVs in each Class I area that could be affected by the new source?
- What are the air pollutant doses that may affect the identified sensitive AQRVs?

- Will the proposed facility result in pollutant concentrations or atmospheric deposition that will cause the identified critical dose to be exceeded?

- If the critical dose is exceeded, what amount of additional pollution is considered "insignificant"?

Table I-2.  Prevention of significant deterioration increments (in $\mu g/m^3$); PSD increments are not defined for ozone.

| Constituent | Averaging Time | Class I | Class II | Class III |
|---|---|---|---|---|
| | Annual Arith. Mean | 2 | 20 | 40 |
| | 24-hour | 5 | 91 | 182 |
| Sulfur Dioxide | 3-hour | 25 | 512 | 700 |
| | Annual Arith. Mean | 4 | 17 | 34 |
| PM-10 | 24-hour | 8 | 30 | 60 |
| Nitrogen Dioxide | Annual Arith. Mean | 2.5 | 25 | 50 |

The first two questions are land management issues that should be answered on the basis of management goals and objectives for the Class I area.  The last two are technical questions that must be answered on the basis of analyses of emissions from the proposed facility and predictions of environmental response to a given pollutant concentration (Peterson et al. 1992).

**3.    Gaseous Pollutants of Concern**

a.    Ozone

Ozone is a secondary pollutant formed by the photooxidation of nitrogen oxides ($NO_x$) and volatile organic compounds (VOCs).  Ozone is a colorless gas and is a component of photochemical haze which can develop during the clear warm weather associated with high pressure systems.  Ozone is an important regional pollutant because it forms during transport of its precursors (VOC and $NO_x$), and can occur at high concentrations in areas remote from precursor sources.  The level of ozone in a "pristine" area may be as low as 10 to 25 ppbv (weekly average) (Altshuller and Lefohn 1996, Cooper and Peterson 1996).  Areas in the southeastern United States and southern California experience ozone concentrations exceeding 150 to 200 ppbv (maximum hourly concentrations).  Ozone is a potential threat to high-elevation plant species because concentrations tend to increase with elevation (Loibl et al. 1994; Sandroni et al. 1994; Brace and Peterson 1996,1998).

Ozone causes injury to highly sensitive species of plants at concentrations as low as 60 ppbv (Treshow and Anderson 1989).  Ozone enters plant leaves as a gas and dissolves in the presence of water.  The resulting free radicals oxidize proteins of cell membranes, including those of the thylakoid membranes where photosynthesis takes place.  Injury includes leaf discoloration, reduced photosynthesis rates, lowered sugar production, reduced growth and possibly death.

b.    Sulfur Dioxide

Sulfur dioxide ($SO_2$) is a product of fossil fuel production.  Some of the largest emitters are coal-fired electric power plants and smelters.  Forest dieback near power plants has been documented since the mid 1800s.  Although more stringent regulations have reduced emissions over the last 50 years, $SO_2$ continues to be a major pollutant of concern in many areas of the United States.  $SO_2$ is a precursor of pollutants which cause acidic deposition and visibility impairment.

Like ozone, $SO_2$ is a gas and enters the leaf through the stomata.  Inside the leaf it disrupts mesophyll cell functioning causing reduced productivity of the leaf.  $SO_2$ injury in plants is characterized by leaf bleaching and chlorosis, necrotic lesions, and early senescence.  Prolonged exposure can weaken a plant making it susceptible to pathogens and other organisms.  Some species are sensitive to chronic exposures of as low as 25 ppbv (Treshow and Anderson 1989).

There are few data on the effects of sulfur compounds on mature trees or other native plants, and there is a wide range of sensitivities to ambient S compounds (Davis and Wilhour 1976, Smith

1990). Limited data on tree seedlings (Hogsett et al. 1985, P.R. Miller unpublished data) indicate that $SO_2$ concentrations below 20 ppbv (24-hour mean) do not produce visible injury symptoms. For ponderosa pine (*Pinus ponderosa*) and lodgepole pine (*P. contorta*), slight injury is found with chronic exposures above 40 ppbv and moderate injury above 65 ppbv. Slight injury is found for Douglas-fir (*Pseudotsuga menziesii*) above 65 ppbv. In order to maximize protection of all plant species, acute $SO_2$ concentrations should not exceed 40 to 50 ppbv, and annual average 24-hour $SO_2$ concentrations should not exceed 8 to 12 ppbv.

c.   Fluoride

Fluoride occurs naturally at low levels in soils, air, and water, and it also is emitted through industrial processes including aluminum manufacturing. Fluoride occurs in two forms, gaseous (HF) and particulate. Soil fluoride is mainly in particulate form and increases in concentration with increased soil acidity. The background level of fluoride in most soils ranges between 0.05% and 1%. Particulate fluoride is less readily absorbed by plants than the gaseous form. Background levels of fluoride in plants are around 2 to 20 ppm (Treshow and Anderson 1989). Plant tissues accumulate fluoride and sensitive species may begin to show symptoms of damage at levels around 30 to 50 ppm (Treshow and Anderson 1989). Marginal leaf necrosis is the classic symptom of fluoride toxicity. Other symptoms in plants include leaf tip burn, chlorosis, necrotic spotting, accelerated foliar senescence, and reduced growth rates (Treshow and Anderson 1989, Smith 1990).

d.   Hydrogen Sulfide

Hydrogen sulfide ($H_2S$) is a highly toxic gas that is formed by the decomposition of organic matter containing sulfur. It is found in mines, wells, sewers, cesspools, natural gas, volcanic gas and in some spring waters. It is a colorless, flammable gas with a density greater than that of air. The "rotten egg" odor of $H_2S$ gas is one of the most easily detectable odors to the human nose with an odor threshold less than 5 ppbv (Weiss 1986). Concentrations between 20 and 150 ppmv cause irritation of the eyes and slightly higher concentrations cause irritation of the upper respiratory tract (Sax and Lewis 1989). Exposures of between 600 and 1000 ppmv may be fatal to humans within 30 minutes. It is highly corrosive to standard metals and causes paint discoloration.

Air pollution by $H_2S$ is not a widespread problem but rather is typically localized near emitters such as oil and gas wells, kraft paper mills, sewage treatment plants, petroleum refineries and coke ovens. Background levels for $H_2S$ are estimated to be less than 0.2 ppbv (Smith 1990). Little work has been done on $H_2S$ effects on wildlife and vegetation (Bicknell 1984). Research has focused on the criteria pollutants and therefore $H_2S$ has received only occasional attention, perhaps because $H_2S$ is readily converted to $SO_2$ and sulfate in the atmosphere. However, limited information indicates that $H_2S$ can cause symptoms in some plant species. Douglas-fir was found to show slight

symptoms in response to chronic concentrations as low as 0.1 ppmv and extensive foliar damage to concentrations of 0.3 ppmv (Thompson and Kats 1978). In general, at acute doses of 100 ppmv for 5 hours, angiosperms develop interveinal necrotic blotches while gymnosperms develop distal necrosis (Smith 1990).

e.  VOCs and NO$_x$

Volatile organic compounds (VOCs) and nitrogen oxides (NO$_x$) are not criteria pollutants, but they are important precursors of ozone. NO$_x$ is also a precursor for pollutants that cause acidic deposition and visibility impairment, and VOCs can contribute to visibility impairment. Automobiles and stationary fossil fuel burning systems are the major anthropogenic sources of NO$_x$ in the United States. Naturally occurring NO$_x$ compounds originate from soils, wildfire, lightning and decomposition. Biogenic sources of NO$_x$ are comparable to or less than anthropogenic sources in most areas.

Anthropogenic sources of VOCs include motor vehicle exhaust, gasoline vapors, stationary fuel combustion, commercial and industrial  processes, and emissions from solid wastes (Smith 1990). Natural systems, particularly soils and vegetation, produce VOCs and emit them to the atmosphere; trees in particular emit the highly reactive hydrocarbons isoprene and terpene. Globally, biogenic sources of VOC exceed anthropogenic sources while in localized, urban areas anthropogenic sources typically dominate. VOCs include a large number of hydrocarbons which vary greatly in reactivity.

## 4. Vegetation and Bioindicators

Although acidic deposition was originally cited as a likely cause of reduced vigor in some forests, oxidants can reduce photosynthesis, growth, and productivity of sensitive plant species, even at relatively low exposure levels (Reich and Amundson 1985) and are a more likely stressor of vegetation in much of North America. Chronic exposure to ozone can cause substantial loss of vigor, which can in turn lead to greater susceptibility to additional stresses. The fact that ozone concentrations are often higher downwind from urban areas and that concentrations tend to increase with elevation, suggests that national park lands can be particularly vulnerable. Despite known general relationships between regional "sources" of ozone (and its precursors) with wildland "receptors", it has been extremely difficult to estimate ozone exposure in those wildlands because of a sparse dataset collected primarily in urban areas. Only limited on-site data are available in mountainous locations. In addition, identification of possible symptoms of air pollutant injury is difficult, because visual symptoms are generally poorly documented for vegetation in western North America. The physiological functions of some lichen species are affected by air pollutants, but diagnostic symptoms are difficult to quantify in the field.

Bioindicators are those species for which pollutant sensitivity has been documented and for which data exist on their dose-response to pollutants and on symptomatology. In some cases, bioindicators detect exposure of a pollutant at a site where air quality monitoring data are not available. Ozone and $SO_2$ are the most extensively studied pollutants regarding impacts on vegetation. Much of this work has been conducted on species native to the northeastern and southwestern United States, and little work has been conducted on species of the Rocky Mountain and Great Plains regions.

Pollutants can cause injury to various plant tissues including leaves, stems and roots. Foliar injury is the most visible form of injury, although it often can be confused with pathogen or fungal diseases. Ozone symptoms in conifer and hardwood foliage that could be considered "typical" include chlorosis, stipple (uniform black spots) and accelerated needle and leaf loss (Miller et al. 1983, Hogsett et al. 1989, Treshow and Anderson 1989). Sulfur dioxide-induced injury includes dieback of leaf and needle tips and necrotic spots (Treshow and Anderson 1989). There are few data on the effects of $NO_2$ on plant species, and existing information stems from scattered studies in Europe and the United States.

Sensitivity classes can be used to relate potential foliar injury in trees to pollutant exposures for ozone (Tables I-3 and I-4). These sensitivity classes can be used to identify severity of injury as well as to indicate potential injury thresholds. Any visible injury symptom can be considered a significant impact, regardless of sensitivity class. If pollutant concentrations listed in the tables are reached, then special attention should be directed at identifying injury symptoms. Ozone-sensitivity tables are a rough guideline in which injury level and/or pollutant exposure are keyed to the general sensitivity of a sensitive receptor.

Table I-3. Sensitivity classes for conifers in relation to ozone exposure. (Source: after Peterson et al. 1992)

| Sensitivity class | Needle age class with chlorotic mottle (years) | Needle retention as percent of normal (%) | Ozone concentration (7-hour growing season mean) (ppbv)[a] |
|---|---|---|---|
| Low | $\geq 5$ | 71-80 | 61-70 |
| Medium | 3-4 | 41-70 | 71-90 |
| High | 1-2 | < 40 | > 90 |

[a] Highest continuous 7-hr period

Table I-4. Sensitivity classes for hardwoods in relation to ozone exposure.

| (Source: after Peterson et al. 1992) | | |
|---|---|---|
| Sensitivity class | Percent leaf area with stippling | Ozone concentration (7-hour growing season mean) (ppbv)[a] |
| Low | 21-40 | 71-90 |
| Medium | 41-60 | 91-120 |
| High | 60-100 | >120 |
| [a] Highest continuous 7-hr period | | |

Ozone-sensitivity classes for conifers are based primarily on symptomatology of ponderosa pine (*Pinus ponderosa*) in California (in the field and under experimental conditions) (Miller and Millecan 1971, Pronos and Vogler 1981, Peterson and Arbaugh 1988, Peterson et al. 1991, Peterson and Arbaugh 1992). Because these data are from quantitative studies at a variety of locations, Table I-3 should be quite relevant for assessing ozone injury in ponderosa pine. Applicability to other coniferous species may vary considerably with respect to specific symptoms and pollutant exposure.

Ozone-sensitivity classes for hardwoods are based primarily on data for quaking aspen (*Populus tremuloides*) and a few other hardwood species. Numerous studies have documented the sensitivity of this species to ozone under field and experimental conditions (Wang et al. 1986, Karnosky et al. 1992, Coleman et al. 1996) although there is considerable variability in sensitivity among different genotypes (Berrang et al. 1986). Diagnostic ozone symptomatology for aspen includes chlorosis, stippling, necrotic spotting, and leaf margin burn. Symptoms generally vary seasonally, with stippling being most prominent in the spring and black, bifacial (both leaf surfaces) necrosis appearing in late summer (J.P. Bennett, pers. comm.). Great care must be taken in distinguishing ozone symptoms from various pathogens and insect herbivores commonly found on this species. Table I-4 should be relevant for assessing ozone injury in aspen. Applicability to other hardwood species may vary considerably with respect to specific symptoms and pollutant exposure.

There are few data on potential $SO_2$- and $NO_2$-induced injury to tree species of the Rocky Mountains and Great Plains. Sensitivity and general exposure guidelines for $SO_2$ and $NO_2$ are based on relatively few data and sources of information and include a large amount of subjective judgment based on expert opinion (Peterson et al. 1992). For this reason, we do not present such guidelines. Any evaluation of potential pollutant impacts should consider the fact that some species are more affected by episodic, high concentrations, while other species are more affected by long-term, chronic exposures.

There are no data on injury symptoms for lichens growing in the Rocky Mountain and Great

Plains regions.  Data from studies done in other regions provide general information on sensitivity of lichens to ozone and $SO_2$ but very little information exists on lichen sensitivity to nitrogen.  Three sensitivity classes of lichens can be defined as low, medium and high (Table I-5).  These classes are based on limited experimental data and should be regarded as general when applied to field situations.

| Table I-5.   Sensitivity classes for lichens based on prolonged exposure.  (Source: Peterson et al. 1992) | | |
|---|---|---|
| Sensitivity classes | Ozone concentration (ppbv, 24-hr growing season mean) | $SO_2$ concentration (ppbv, 24-hr growing season mean) |
| Low | >65 | >30 |
| Medium | 15-70 | 10-35 |
| High | <20 | 5-15 |

Nitrogen is a critical nutrient for many plant metabolic processes.  Long-term deposition of elevated levels of N compounds may affect soil microbiological processes, resistance to insects and pathogens, winter injury in conifers, and foliar leaching.  Perhaps more important are the potential effects of long-term N deposition on ecosystem structure and diversity.  Nitrogen is a potential fertilizer that can be assimilated preferentially by some plant species (Miller et al. 1976); for example, increased N deposition could cause plant species in a N-poor system (e.g., a bog) to be replaced by species with higher N requirements.

5.    **Aquatic Resources and Sensitive Indicators**

The potential effects of S deposition on surface water quality have been well studied throughout the United States, particularly within the Environmental Protection Agency's (EPA's) Aquatic Effects Research Program (AERP), a component of the National Acid Precipitation Assessment Program (NAPAP).  Major findings were summarized in a series of State of Science and Technology Reports (e.g., Baker et al. 1990, Sullivan 1990) and the final NAPAP policy report, the 1990 Integrated Assessment (NAPAP 1991).  Although aquatic effects from N deposition have not been studied as thoroughly as those from S deposition, concern has been expressed regarding the role of nitrate ($NO_3^-$) in acidification of surface waters (particularly during hydrologic episodes), the role of $NO_3^-$ in the long-term acidification process, the contribution of ammonium ($NH_4^+$) from agricultural sources to surface water acidification, and the potential for anthropogenic N deposition to stimulate eutrophication of freshwaters and estuaries (e.g., Sullivan 1993, Wigington et al. 1993, Sullivan et al. 1997)

Atmospheric deposition of S and N (as $NO_3^-$ and as $NH_4^+$, which can be quickly nitrified to $NO_3^-$) often cause increased concentrations of $SO_4^{2-}$ in drainage waters and can, in some cases, cause increased concentrations of $NO_3^-$. An increase in the concentration of either of these mineral acid anions will generally result in a number of additional changes in water chemistry. These can include:

- · increased concentration of base cations ($Ca^{2+}$, $Mg^{2+}$, $K^+$, $Na^+$)
- · decreased concentration of acid neutralizing capacity (ANC)
- · increased concentration of hydrogen ion (H+) (decreased pH)
- · increased concentration of dissolved Al

Increased concentrations of $H^+$ and/or Al occur only in response to higher concentrations of $SO_4^{2-}$ or $NO_3^-$ when ANC has decreased to near or below zero. At higher ANC values, $SO_4^{2-}$ or $NO_3^-$ concentrations are mainly balanced by increasing base cation concentrations and some decrease in alkalinity. High concentrations of $H^+$ or Al can be toxic to fish and other aquatic biota.

If $NO_3^-$ leaches into stream or lakewater as a result of increased N deposition, the result can be eutrophication or acidification. If N is limiting for aquatic primary production, the added $NO_3^-$ will generally result in increased algal productivity, which can cause disruption of aquatic community dynamics. If N is not limiting (P or some other nutrient can be limiting, for example), then the added $NO_3^-$ will remain in solution, possibly leading to acidification.

Surface waters that are sensitive to acidification from acidic deposition of sulfur or nitrogen typically exhibit a number of characteristics. Such characteristics either predispose the waters to acidification and/or correlate with other parameters that predispose the waters to acidification. Although precise guidelines are not widely accepted, general ranges of parameter values that reflect sensitivity are as follows:

Dilute - Waters have low concentrations of all major ions, and therefore specific conductance is low (< 25 $\mu$S/cm). In areas of the West which have not experienced substantial acidic deposition, highly sensitive lakes and streams are often ultradilute, with specific conductance less than 10 $\mu$S/cm.

Acid neutralizing capacity - ANC is low. Acidification sensitivity has long been defined as ANC<200 $\mu$eq/L, although more recent research has shown this criterion to be too inclusive. Waters sensitive to chronic acidification generally have ANC<50 $\mu$eq/L, and waters sensitive to episodic acidification generally have ANC<100 $\mu$eq/L. In the Rocky Mountain region, where acidic deposition is generally low and not expected to increase dramatically, ANC values of 25 $\mu$eq/L and 50 $\mu$eq/L probably protect waters from any foreseeable chronic and episodic acidification, respectively.

Base cations - Concentrations are low in non-acidified waters, but increase substantially in response to acidic deposition. In relatively pristine areas, the concentration of ($Ca^{2+}$ +

$Mg^{2+} + Na^+ + K^+$) in sensitive waters will generally be less than about 50 to 100 $\mu$eq/L.

Organic acids - Concentrations are low in waters sensitive to the effects of acidic deposition. Dissolved organic carbon (DOC) causes water to be naturally low in pH and ANC, or even to be acidic (ANC<0), but also imparts substantial pH buffering at these low pH values. Waters sensitive to acidification from acidic deposition in the West generally have DOC less than about 3 to 5 mg/L.

pH - pH is low, generally less than 6.0 to 6.5 in acid-sensitive waters. In areas that have received substantial acidic deposition, acidified lakes are generally those that had pre-industrial pH between 5 and 6.

Acid anions - Sensitive waters generally do not have large contributions of mineral acid anions (e.g., $SO_4^{2-}$, $F^-$, $Cl^-$) from geological or geothermal sources. In particular, the concentration of $SO_4^{2-}$ in drainage waters would not be substantially higher than could reasonably be attributed to atmospheric inputs, after accounting for probable dry deposition and evapotranspiration.

Physical characteristics - Sensitive waters are usually found at moderate to high elevation, in areas of high relief, with flashy hydrology and minimal contact between drainage waters and soils or geologic material that may contribute weathering products to solution. Sensitive streams are generally low order. Sensitive lakes are generally either small drainage systems or small seepage systems that derive much of their hydrologic input as direct precipitation to the lake surface.

Most lakes receive the majority of their hydrologic input from water that has previously passed through the terrestrial catchment. As long as N retention in the terrestrial system remains high, as is generally the case for forested ecosystems, N concentrations in lakes will remain low in the absence of contributions from land use (e.g., agriculture) or other pollution sources. However, if N retention in the catchment is low and the lake has not yet acidified, N deposition can in some cases increase primary production. This is most likely to happen in groundwater recharge lakes where nutrient inputs are derived largely from deposition to the lake surface. Lakes that are most likely to be low in base cations (therefore potentially sensitive to acid deposition) and also N-limited are often systems overlaying volcanic bedrock (these rocks are often high in P).

In the absence of adequate site-specific research data, computer models can be used to predict pollution effects on aquatic ecosystems and to perform simulations of future ecosystem response (Cosby et al. 1985, Agren and Bosatta 1988). The Model of Acidification of Groundwater in Catchments (MAGIC), a lumped-parameter mechanistic model, has been used throughout North America and Europe and extensively tested against the results of diatom reconstructions and ecosystem manipulation experiments (e.g., Wright et al. 1986; Sullivan et al. 1992; Sullivan and

Cosby 1995; Cosby et al. 1995,1996). Watershed models that include N dynamics should prove valuable to management agencies which require quantitative predictions of pollution impacts and control programs. Nitrogen dynamics have recently been added to the MAGIC model (Jenkins et al. 1997). A new mechanistic model of N dynamics and leaching from forested ecosystems that is currently being extensively tested is the Model of Ecosystem Retention and Leaching of Inorganic Nitrogen (MERLIN; Cosby et al. in press).

## 6. Visibility

The best visibility in the conterminous United States typically occurs in the Great Basin, Colorado Plateau, and Rocky Mountains. The NPS monitors visibility conditions and supports studies to determine the causes of visibility impairment (haze) at many parks and wilderness areas nationwide. The purpose of this monitoring is to characterize current visibility conditions, identify the specific chemical species and their emission sources that contribute to visibility impairment, and to document long-term trends to assess the effects of changes in emissions. The NPS cooperates and shares resources with other federal land management agencies, states, and the U.S. EPA in the Interagency Monitoring of Protected Visual Environments (IMPROVE) program. IMPROVE monitoring is conducted at four (4) NPS Class I areas in the central and northern Rocky Mountains, and northern Great Plains: BADL, GLAC, ROMO, and YELL. Table I-6 summarizes visibility monitoring across the Rocky Mountains and northern Great Plains since 1988.

| | | Visibility Monitoring | | |
|---|---|---|---|---|
| Region | National Park | Particle (Aerosol) | Optical | View |
| Central Rocky Mountains | GRTE | None | None | 9/14/85 - 9/22/91 |
| | ROMO | 3/1/88 - Present | 11/25/87 - Present | 10/25/85 - 4/1/95 |
| | YELL | 3/1/88 - Present | 7/18/89 - 7/28/93 | 9/4/86 - 4/1/95 |
| Northern Rocky Mountains | GLAC | 3/1/88 - Present | 3/1/89 - Present | 6/14/85 - 4/12/95 |
| Northern Great Plains | BADL | 3/1/88 - Present | 1/13/88 - Present | 8/5/87 - 4/11/95 |
| | THRO | None | None | 9/4/85 - 9/20/91 |
| | WICA | None | None | 10/2/85 - 8/11/91 |

Table I-6. Visibility monitoring in Class I National Parks of the central Rocky Mountain, northern Rocky Mountain, and northern Great Plains regions.

Program descriptions and spatial distribution summaries presented in the following sections were extracted from "Spatial and Temporal Patterns and the Chemical Composition of the Haze in the United States: An Analysis of Data from the IMPROVE Network, 1988-1991" (Sisler et al., 1993)

and "Spatial and Seasonal Patterns and Long Term Variability of the Composition of the Haze in the United States: An Analysis of Data from the IMPROVE Network" for 1992-1995 (Sisler et al., 1996).

a.    Visibility Characterization

Visibility is usually characterized by visual range (the greatest distance that a large, black object can be seen against a viewing background) expressed in kilometers (km) or light extinction (the sum of light scattering and absorption per unit distance) expressed in inverse megameters ($Mm^{-1}$).  These two characterizations are inversely related; a visual range (VR) of 391 km signifies the best possible visibility and corresponds to a light extinction ($b_{ext}$) of 10 $Mm^{-1}$; as visual range decreases, light extinction increases.  Neither visual range nor extinction is linear with respect to increases or decreases in perceived visual air quality.  For example, a 15 km change in visual range or 2 $Mm^{-1}$ change in extinction can result in a scene change either unnoticeably small or very apparent depending on the baseline visibility conditions.  Therefore, a third visibility characterization, the deciview (dv), was derived by Pitchford and Malm (1994) to index a constant fractional change in extinction or visual range.  The advantage of this characterization is that equal changes in deciview are equally perceptible across different baseline conditions. Higher deciview values signify poorer visibility.  A zero deciview corresponds to Rayleigh scattering (clean air), 10 $Mm^{-1}$, or a visual range of 391 km.

Of the three visibility indices, the light extinction coefficient ($b_{ext}$, commonly called extinction) is the characterization most used by scientists concerned with causes of reduced visibility.  Extinction can be directly calculated from light transmittance measurements (measured extinction) or derived from measured particle concentrations (reconstructed extinction).  Direct relationships exist between the concentrations of particles and gases and their contribution to the extinction coefficient.  Understanding these relationships provides a method of estimating how visibility would change with changes in the concentrations of these atmospheric constituents.  This methodology known as "extinction budget analysis," is important for assessing the visibility consequences of proposed pollutant emission sources, or for determining the extent of pollution control required to meet a desired visibility condition. Extinction, both measured and reconstructed, is the primary visibility characterization provided in this report.

b.    Mechanisms and Sources of Visibility Impacts

Visibility impairment results from both scattering and absorption of light by gases and particles suspended in the air.  Light scattering results from the natural Rayleigh scatter from air molecules (which causes the blue sky) and the scattering caused by suspended particles in the atmosphere (aerosols).  Rayleigh scatter is approximately 10 $Mm^{-1}$, but varies with altitude and the associated density of the atmosphere.  Particle scatter can be caused by natural aerosols (e.g., wind-blown dust

and fog) or by man-made aerosols (e.g., sulfates, nitrates, organics, and other fine and coarse particles).  The effect of particle scatter depends on the particle size, chemical properties, hygroscopic properties, and mass concentration of the particles in the atmosphere. Fine particles have the largest effect on visibility.  Fine particles with sizes near the light wavelengths of visible light (0.4 - 0.7 $\mu$m) are the most efficient light scatterers.  In addition, when water is associated with sulfates, nitrates, and some organics, the total light scattering can increase substantially over corresponding dry conditions.  In most parts of the country, sulfates and organics make up the largest mass fractions of the fine aerosol.  Although not as abundant, nitrates are also a major contributor to visibility impairment.  Coarse particles from natural and man-made sources also affect scattering but have less influence than fine particles.

Gases and particles also absorb light.  Nitrogen dioxide ($NO_2$) is the only major visible light-absorbing gas in the lower atmosphere.  Elemental carbon (soot) is the dominant light-absorbing particle in the atmosphere.  Primary sources of elemental carbon include diesel exhaust and smoke.

With few exceptions, average concentrations of sulfate, organics, and elemental carbon are highest in summer.  Nitrate concentrations are generally highest in winter or spring.  Soil concentrations are highest in spring or summer.


c.    IMPROVE Station Description and Rationale

A fully complemented IMPROVE station could consist of the following; fine and coarse particle (aerosol) monitoring, optical monitoring, and view monitoring with photography.  A brief summary of each follows.


*Particle Monitoring*

Particle monitoring provides concentration measurements of atmospheric constituents that contribute to visibility impairment.  Four independent IMPROVE sampling modules are used to automatically collect two 24-hour samples of suspended particles each week by drawing air through filters.  Three of the four samplers (modules A, B, and C) collect fine particles with diameters <2.5 $\mu$m.  Particles of <2.5 $\mu$m are especially efficient at scattering light.  The fourth sampler (module D) collects coarse particles with diameters up to 10 $\mu$m.  Coarse particles do not scatter light well, and therefore, typically do not contribute much to visibility impairment. The module A, B, and C filters are analyzed to determine the gravimetric mass and chemical composition of the collected particles.  These filters are analyzed specifically to estimate the elemental composition and mass of sulfate, nitrate, and organic and elemental carbon species. In addition, the module A filter is used to estimate the light absorption coefficient ($b_{abs}$).  All data obtained from the IMPROVE sampling modules are used to determine chemical concentrations and to reconstruct extinction  from known extinction efficiencies of certain species.

*Optical Monitoring*

Optical monitoring provides a quantitative measure of light extinction to represent visibility conditions. Water vapor in combination with suspended particles can affect visibility, so optical stations also record temperature and relative humidity. Optical monitoring uses ambient, long-path transmissometers and ambient nephelometers to collect hourly-averaged data. Transmissometers measure the amount of light transmitted through the atmosphere over a known distance (between 0.5 and 10.0 km) between a light source of known intensity (transmitter) and a light measurement device (receiver). The transmission measurements are electronically converted to hourly averaged light extinction. Ambient nephelometers draw air into a chamber and measure the scattering component of light extinction. Data from both of these instruments are recovered at a central location for storage and analyses. Optical measurements of extinction and scattering include meteorological events such as cloud cover and rain, however, the data are "filtered" by flagging invalid data points with high relative humidities (RH>90%). This filtering process is assumed to remove the effects of weather from the data set. Although nephelometer monitoring has been conducted for special studies performed in the Rocky Mountains area, no nephelometer monitoring has been conducted for any individual NPS Class I area in the Central or Northern Rocky Mountains or Northern Great Plains regions.

*View Monitoring*

View monitoring is accomplished with automated 35mm camera systems. Cameras typically take three photographs a day (9:00, 12:00, and 15:00) of selected scenes. The resulting slides are used to facilitate data interpretation, and form a photographic record of characteristic visibility conditions. Based on April 1995 recommendations of the IMPROVE Steering Committee, view monitoring has been discontinued at all NPS Class I areas that have a five year (or greater) photographic monitoring record. No view monitoring has been conducted at any Central or Northern Rocky Mountains or Northern Great Plains region visibility monitoring site since April 1995.

The IMPROVE monitoring network currently consists of 55 sites with various configurations of particle, optical, and view monitoring equipment. Five IMPROVE sites are located in the Central Rocky Mountains Region, one site in the Northern Rocky Mountains Region, and one site in the Northern Great Plains Region. A detailed description of the entire IMPROVE visibility and particle monitoring network may be found in Sisler et al. (1996).

d.    Overview of Visibility Conditions

Particle, optical, and view monitoring data for the Central Rocky Mountains, Northern Rocky Mountains, and Northern Great Plains regions were extracted from IMPROVE network data archives and summarized for the March 1988  through February 1995 period.

Figure I-1 summarizes the spatial distribution of total reconstructed light extinction (including Rayleigh) averaged by site over three years (March 1992 through February 1995), as presented in "Spatial and Seasonal Patterns and Long Term Variability of the Composition of the Haze in the United States: An Analysis of Data from the IMPROVE Network" for 1992-1995 (Sisler et al., 1996). Figure I-2 provides a graphic summary of measured light extinction by geographic region and by season for the period March 1988 through February 1995.  Seasonal arithmetic means of regional IMPROVE transmissometer data were summarized by the following visibility metric categories:

- Worst - conditions represent a mean visual range less than 41 km ($b_{ext}$ >95 $Mm^{-1}$)

- Below Average - conditions represent a mean visual range from 41 km to 78 km ($b_{ext}$ from 95 $Mm^{-1}$ to 50 $Mm^{-1}$)

- Above Average - conditions represent a mean visual range from 78 km to 145 km ($b_{ext}$ from 50 $Mm^{-1}$ to 27 $Mm^{-1}$)

- Best - conditions represent a mean visual range greater than 145 km ($b_{ext}$ <27 $Mm^{-1}$)

For both time periods, the highest reconstructed or measured light extinction

($>100$ Mm$^{-1}$) occurred in the eastern United States while the Colorado Plateau and the Great Basin regions had the lowest light extinction ($< 27$ Mm$^{-1}$).

IMPROVE network particle and optical (transmissometer) monitoring sites represented in Figures I-1 and I-2 respectively are listed by geographic region in Table I-7.  Site-specific seasonal and annual averages of reconstructed and measured extinction for the period March 1988 through February 1995 are provided in Tables I-8 and I-9.  Caution should be used when comparing reconstructed and measured extinction.  Given differences in measurement periods and averaging methods, as well as relative humidity filtering methods and effects on light extinction efficiencies, the ratio of reconstructed extinction to measured extinction is seldom greater than 80%.

Tables I-8 and I-9 summarize the seasonal and annual averages of reconstructed light extinction coefficients for Central and Northern Rocky Mountains and Northern Great Plains regions (March 1988 through February 1995).  It should be noted that these data are from one or two sites in each region and may not be representative of the entire regional area.  Table I-8 also shows the breakdown of non-Rayleigh extinction among fine and coarse particle scattering, and absorption.

Figure I-2.    Seasonal visibility across the continental United States calculated using $b_{ext}$ data from each operational transmissometer site in the IMPROVE network for the period March 1988 through February 1995.
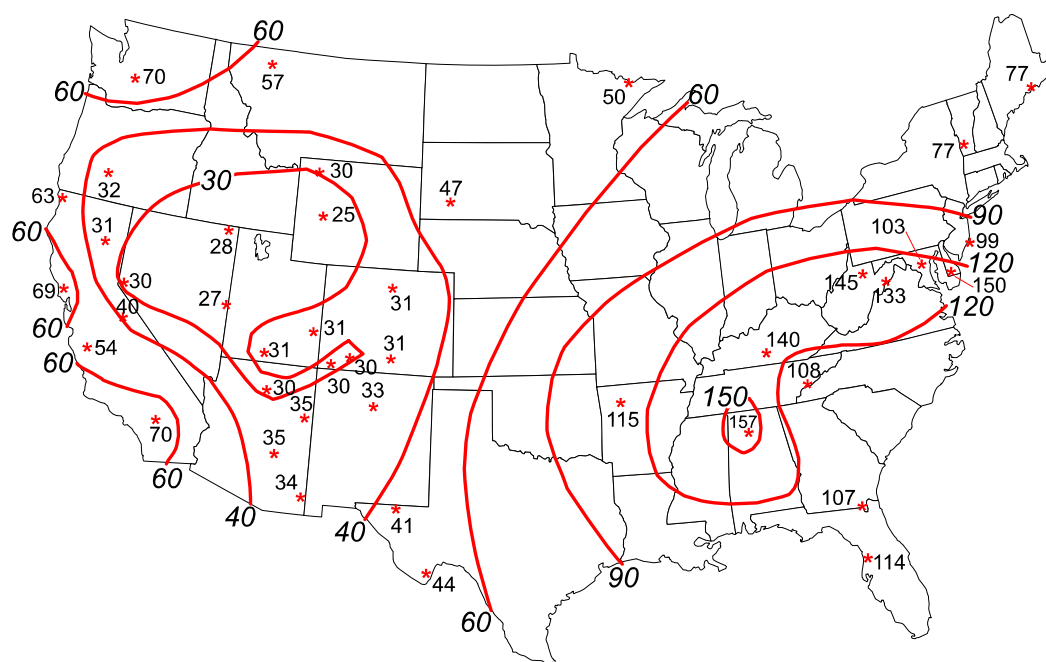
Table I-7.  Operational particle and optical monitoring sites of the IMPROVE monitoring
network March 1988 through February 1995 by geographic region.

**Alaska**
· Denali NP (A)

**Appalachian Mountains**
· Great Smoky Mountains NP (AN)
· Shenandoah NP (AT)
· Dolly Sods WA (AN)

**Boundary Waters**
· Boundary Waters Canoe Area (AN)

**Cascade Mountains**
· Mount Rainier NP (AN)

**Central Rocky Mountains**
· Bridger WA (AT)
· Great Sand Dunes NM (A)
· Rocky Mountain NP (AT)
· Weminuche WA (A)
· Yellowstone NP (AT)

**Coastal Mountains**
· Pinnacles NM (A)
· Point Reyes (A)
· Redwood NP (A)

**Colorado Plateau**
· Bandelier NM (AT)
· Bryce Canyon NP (A)
· Canyonlands NP (AT)
· Grand Canyon NP (ATN)
· Mesa Verde NP (A)
· Petrified Forest NP (AT)

**Florida**
· Chassahowitzka NWR (A)
· Okefenokee NWR (AN)

**Great Basin**
· Jarbidge WA (AN)
· Great Basin NP (AT)

**Lake Tahoe**
· D.L. Bliss State Park (ATN)
· South Lake Tahoe (AN)

**Mid Atlantic**
· Edmond B. Forsythe NWR (AN)

**Mid South**
· Upper Buffalo WA (AN)
· Sipsey WA (A)
· Mammoth Cave NP (AN)

**Northeast**
· Acadia NP (AN)
· Lye Brook WA (AN)

**Northern Great Plains**
· Badlands NP (AT)

**Northern Rocky Mountains**
· Glacier NP (AT)

**Sierra Nevada**
· Yosemite NP (AT)

**Sierra-Humboldt**
· Crater Lake NP (A)
· Lassen Volcanoes NP (A)

**Sonoran Desert**
· Chiricahua AZ (AT)
· Tonto NM (A)

**Southern California**
· San Gorgonio WA (AT)

**Washington, D.C.**
· Washington, D.C. (A)

**West Texas**
· Big Bend NP (AT)
· Guadelupe Mountains NM (AT)

NP = National Park
NM = National Monument
WA = Wilderness Area
NWR = National Wildlife Refuge
NS = National Seashore

A = Aerosol Sampler
T = Transmissometer
N = Nephelometer

| Season | Total Extinction | Natural Rayleigh Extinction | Non-Rayleigh Extinction | Fine Scattering | Coarse Scattering | Absorption |
|---|---|---|---|---|---|---|
| **Table I-8.** Seasonal and annual average reconstructed light extinction ($Mm^{-1}$) apportioned by general category for the central Rocky Mountain, northern Rocky Mountain, and northern Great Plains regions (March 1988 through February 1995). | | | | | | |
| Central Rocky Mountains | | | | | | |
| Spring | 32.2 | 10.0 | 22.2 | 14.7 | 3.0 | 4.5 |
| Summer | 40.4 | 10.0 | 30.4 | 16.6 | 5.9 | 7.9 |
| Autumn | 30.8 | 10.0 | 20.8 | 12.8 | 3.2 | 4.8 |
| Winter | 23.6 | 10.0 | 13.6 | 9.2 | 1.9 | 2.5 |
| Annual | 31.7 | 10.0 | 21.7 | 13.2 | 3.6 | 4.9 |
| Northern Rocky Mountains | | | | | | |
| Spring | 48.7 | 10.0 | 38.7 | 27.5 | 3.6 | 7.6 |
| Summer | 50.1 | 10.0 | 40.1 | 25.1 | 6.4 | 8.6 |
| Autumn | 65.8 | 10.0 | 55.8 | 38.6 | 5.1 | 12.2 |
| Winter | 66.9 | 10.0 | 56.9 | 45.8 | 2.2 | 8.8 |
| Annual | 57.1 | 10.0 | 47.1 | 33.5 | 4.3 | 9.3 |
| Northern Great Plains | | | | | | |
| Spring | 50.4 | 10.0 | 40.4 | 29.6 | 4.1 | 6.7 |
| Summer | 48.3 | 10.0 | 38.3 | 25.3 | 5.4 | 7.6 |
| Autumn | 40.2 | 10.0 | 30.2 | 20.0 | 4.2 | 6.0 |
| Winter | 45.5 | 10.0 | 35.5 | 27.9 | 2.7 | 4.9 |
| Annual | 46.0 | 10.0 | 36.0 | 25.6 | 4.1 | 6.3 |

| Season | Non-Rayleigh Aerosol Extinction | Sulfate | Nitrate | Organics | Elemental Carbon (Absorption) | Soil & Coarse Material |
|---|---|---|---|---|---|---|
| **Central Rocky Mountains** | | | | | | |
| Spring | 22.2 | 7.1 | 2.5 | 5.1 | 4.5 | 3.0 |
| Summer | 30.4 | 6.3 | 1.3 | 9.1 | 7.9 | 5.9 |
| Autumn | 20.8 | 5.0 | 1.4 | 6.4 | 4.8 | 3.2 |
| Winter | 13.6 | 3.2 | 1.5 | 4.5 | 2.5 | 1.9 |
| Annual | 21.7 | 5.3 | 1.6 | 6.3 | 4.9 | 3.6 |
| **Northern Rocky Mountains** | | | | | | |
| Spring | 38.7 | 14.4 | 3.1 | 10.0 | 7.6 | 3.6 |
| Summer | 40.1 | 11.1 | 1.8 | 12.3 | 8.6 | 6.4 |
| Autumn | 55.8 | 15.0 | 4.9 | 18.7 | 12.2 | 5.1 |
| Winter | 56.9 | 21.2 | 12.4 | 12.3 | 8.8 | 2.2 |
| Annual | 47.1 | 15.3 | 4.9 | 13.2 | 9.3 | 4.3 |
| **Northern Great Plains** | | | | | | |
| Spring | 40.4 | 18.1 | 5.6 | 5.9 | 6.7 | 4.1 |
| Summer | 38.3 | 15.2 | 1.4 | 8.7 | 7.6 | 5.4 |
| Autumn | 30.2 | 10.6 | 2.7 | 6.6 | 6.0 | 4.2 |
| Winter | 35.5 | 14.3 | 8.7 | 5.0 | 4.9 | 2.7 |
| Annual | 36.0 | 14.6 | 4.4 | 6.6 | 6.3 | 4.1 |

Table I-9. Contributions of various types of fine particles (Mm$^{-1}$) to the total seasonal and annual average non-Rayleigh aerosol light extinctions for the central Rocky Mountain, northern Rocky Mountain, and northern Great Plains regions (March 1988 through February 1995).

Table I-9 further identifies the contributions of sulfate, nitrate, organics, elemental carbon, and coarse particles (including fine soil) to the non-Rayleigh aerosol light extinction.

Figure I-3 graphically depicts the percentage of total light extinction (including Rayleigh) contributed by sulfate, nitrate, organics, elemental carbon, and coarse particles.

*Central Rocky Mountains*

Aerosol and optical measurements presented for this region were made at two locations in the mountainous Class I areas of Colorado and Wyoming at ROMO and YELL. The annual average total reconstructed extinction for the central Rocky Mountains for the March 1988 through February 1995 period is 31.7 Mm$^{-1}$, of which, 68% is due to aerosol extinction. The seasonal variation is significant with a maximum total extinction of 40.4 Mm$^{-1}$ in summer and a minimum of 23.6 Mm$^{-1}$ during winter. The seasonal variance is driven primarily by organic extinction and absorption. Organic extinction peaks at 9.1 Mm$^{-1}$ in summer and drops to 4.5 Mm$^{-1}$ in winter. Absorption (elemental carbon) ranges from 7.9 Mm$^{-1}$ in summer to 2.5 Mm$^{-1}$ in winter. Organics are the largest

contributor to aerosol extinction during the summer months at 29.9%.  Absorption follows closely

Figure I-3   Annual average percentage of total light extinction (including Rayleigh) contributed by sulfate, nitrate, organics, elemental carbon, and coarse particles for the central Rocky Mountain, northern Rocky Mountain, and northern Great Plains regions (March 1988 through February 1995).

**Central Rocky Mountains Region**
Total Reconstructed Extinction = 31.7 Mm$^{-1}$

Soil & Coarse 11%
Rayleigh Extinction 32%
Elemental Carbon 15%
Organics 20%
Nitrate 5%
Sulfate 17%



**Northern Rocky Mountains Region**
Total Reconstructed Extinction = 57.1 Mm$^{-1}$

Soil & Coarse 8%
Rayleigh Extinction 18%
Elemental Carbon 16%
Organics 23%
Nitrate 9%
Sulfate 26%



**Northern Great Plains Region**
Total Reconstructed Extinction = 46.0 Mm$^{-1}$

Soil & Coarse 9%
Rayleigh Extinction 22%
Elemental Carbon 14%
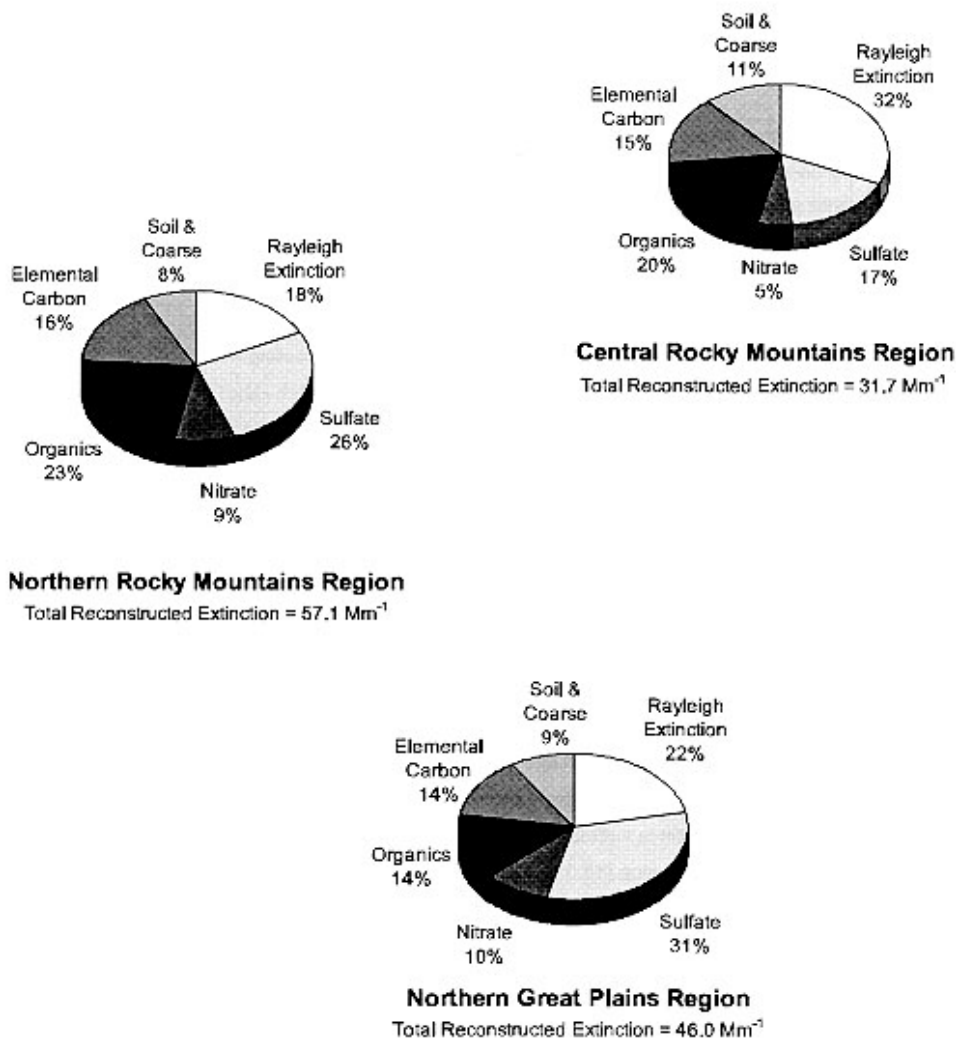Organics 14%
Nitrate 10%
Sulfate 31%

Figure I-3   Annual average percentage of total light extinction (including Rayleigh) contributed by sulfate, nitrate, organics, elemental carbon, and coarse particles for the central Rocky Mountain, northern Rocky Mountain, and northern Great Plains regions (March 1988 through February 1995).

behind at 25.9%.  Organics are also the largest contributor to annual aerosol extinction (29%), followed by sulfates (24.4%), absorption (22.6%), coarse mass (16.6%), and nitrate (7.3%).

*Northern Rocky Mountains*

This region is represented by one site close to the U.S./Canada border, GLAC. Aerosol monitoring and optical monitoring was conducted at the site.  The annual average total reconstructed light extinction for the March 1988 through February 1995 period is 57.1 $Mm^{-1}$, of which 82% is due to aerosol extinction.  A modest seasonality of total extinction occurs, ranging between 66.9 $Mm^{-1}$ in winter to 48.7 $Mm^{-1}$ during spring.  The seasonal variance is driven primarily by sulfate and nitrate extinction. Sulfate and nitrate extinctions peak during winter at 21.2 $Mm^{-1}$ and 12.4 $Mm^{-1}$, respectively, and drop to 11.1 $Mm^{-1}$ and 1.8 $Mm^{-1}$ in summer.  The largest contributor to annual aerosol extinction is sulfate (32.5%), followed by organics (28%), and absorption (elemental carbon, 19.7%).

*Northern Great Plains*

This region is represented by only one Class I area in South Dakota, BADL.  Aerosol and optical monitoring were both conducted at this site. The annual average total reconstructed light extinction averaged 46.0 $Mm^{-1}$ for the March 1988 through February 1995 period.  Unlike most other regions, extinction was highest in spring and lowest in autumn.  Seasonal variance is driven primarily by sulfate and nitrate extinction.  Sulfate extinction peaks at 18.1 $Mm^{-1}$ in spring and drops to 10.6 $Mm^{-1}$ in autumn. Nitrate extinction in spring, at 5.6 $Mm^{-1}$, is more than four times its summer extinction of 1.4 $Mm^{-1}$.  The maximum nitrate extinction of 8.7 $Mm^{-1}$ occurs in winter.  The main contributor to annual extinction is sulfate, which accounts for 40.5% of the aerosol extinction. The next highest contributor is organics (18.3%), followed closely by absorption (elemental carbon 17.5%), nitrate (12.2%), and coarse mass (11.4%).
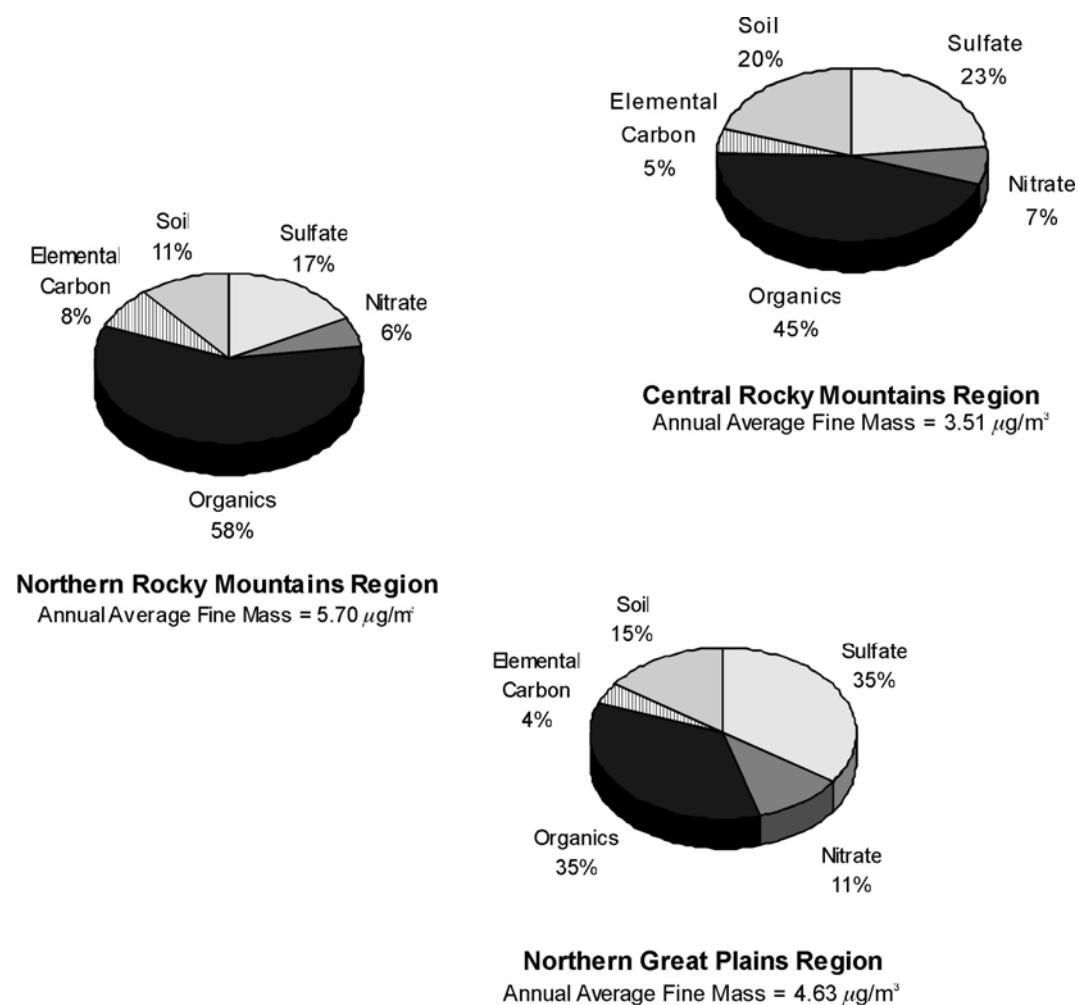
Table I-10 shows the mass concentrations ($\mu g/m^3$) of fine and coarse aerosol, and the chemical composition (mass budgets) of fine aerosol for the Central Rocky Mountains, Northern Rocky Mountains, and Northern Great Plains regions.  It should be noted that these data are from one or two sites in each region and may not be representative of the entire regional area.

Figure I-4 graphically depicts the measured fine aerosol mass budgets (in percent) for each region.  These summaries represent the seasonal and annual mean concentrations for the March 1988 through February 1995 period.

| Season | Fine Mass | Sulfate | Nitrate | Organics | Elemental Carbon | Soil | Coarse Mass |
|---|---|---|---|---|---|---|---|
| **Table I-10.** Measured fine and coarse aerosol mass concentrations (in $\mu g/m^3$) for the central Rocky Mountains, northern Rocky Mountains, and northern Great Plains (March 1988 through February 1995). | | | | | | | |

Table I-10. Measured fine and coarse aerosol mass concentrations (in $\mu g/m^3$) for the central Rocky Mountains, northern Rocky Mountains, and northern Great Plains (March 1988 through February 1995).

| Season | Fine Mass | Sulfate | Nitrate | Organics | Elemental Carbon | Soil | Coarse Mass |
|---|---|---|---|---|---|---|---|
| Central Rocky Mountains | | | | | | | |
| Spring | 3.58 | 0.95 | 0.35 | 1.27 | 0.13 | 0.87 | 3.57 |
| Summer | 4.78 | 0.97 | 0.20 | 2.27 | 0.25 | 1.10 | 8.04 |
| Autumn | 3.36 | 0.77 | 0.21 | 1.60 | 0.18 | 0.60 | 4.39 |
| Winter | 2.31 | 0.58 | 0.27 | 1.13 | 0.13 | 0.21 | 2.86 |
| Annual | 3.51 | 0.82 | 0.26 | 1.57 | 0.17 | 0.70 | 4.83 |
| Northern Rocky Mountains | | | | | | | |
| Spring | 4.71 | 1.06 | 0.23 | 2.50 | 0.33 | 0.59 | 4.96 |
| Summer | 5.40 | 0.94 | 0.15 | 3.07 | 0.34 | 0.91 | 9.14 |
| Autumn | 7.30 | 1.97 | 0.32 | 4.67 | 0.63 | 0.71 | 7.27 |
| Winter | 5.50 | 1.03 | 0.60 | 3.07 | 0.53 | 0.26 | 3.26 |
| Annual | 5.70 | 1.00 | 0.32 | 3.31 | 0.45 | 0.62 | 6.21 |
| Northern Great Plains | | | | | | | |
| Spring | 4.99 | 1.94 | 0.60 | 1.47 | 0.17 | 0.81 | 5.50 |
| Summer | 5.21 | 1.80 | 0.16 | 2.18 | 0.19 | 0.87 | 7.55 |
| Autumn | 4.19 | 1.27 | 0.33 | 1.66 | 0.18 | 0.74 | 5.80 |
| Winter | 4.10 | 1.42 | 0.86 | 1.25 | 0.18 | 0.38 | 3.85 |
| Annual | 4.63 | 1.61 | 0.49 | 1.64 | 0.18 | 0.70 | 5.69 |

Figure I-4.    Annual average measured fine aerosol mass budgets (in percent) for the central Rocky
Mountains, northern Rocky Mountains, and northern Great Plains regions (March 1988
through February 1995).



**Central Rocky Mountains Region**
Annual Average Fine Mass = 3.51 $\mu$g/m$^3$

**Northern Rocky Mountains Region**
Annual Average Fine Mass = 5.70 $\mu$g/m$^3$

**Northern Great Plains Region**
Annual Average Fine Mass = 4.63 $\mu$g/m$^3$

e.    Visibility Special Studies for the Central Rocky Mountains Region

In addition to the IMPROVE network, the Central Rocky Mountains region has been the focus of

two studies that examined visibility, haze, and the sources of pollutants responsible for visibility

impairment.  These studies are:

- The Mount Zirkel Wilderness Area Reasonable Attribution Study of Visibility Impairment
(1996 - 97), was initiated in response to the July 1993 U.S. Forest Service Certification of

Impairment in the Mount Zirkel Wilderness Area (west of ROMO).  The primary goals of the study were to: 1) determine the extent of visibility impairment within the Mount Zirkel Wilderness Area,  2) build a better information base upon which the State could make a reasonable attribution decision regarding visibility impairment at Mount Zirkel Wilderness Area due to the Craig or Hayden power stations, and 3) determine the relative contribution of emissions from each source or group of sources to visibility impairment.  Conclusions of the study stated:  "Visibility (light extinction) in the Mount Zirkel Wilderness Area is among the best measured in U.S. Class I areas.  The Craig and Hayden power plants in northwestern Colorado contribute to air pollution over the Mount Zirkel Wilderness, however, regional pollution sources (i.e., automobiles, coal and oil fired power plants, smelters, and wildfire emissions) appear to be the major contributor to the area's haze problem."

- The Northern Front Range Air Quality Study (1996 - 97, and previous Colorado Front Range studies, 1986-87, 1984, 1978, etc.), whose goals are, and have been, to: 1) determine the sources of existing air pollution in the Denver urban region, 2) estimate particle emissions, particulate precursors, and other substances, and 3) collect data necessary to support informed decision-making concerning the attainment and maintenance of federal National Ambient Air Quality Standards for airborne particles and state visibility goals.  Data analysis for the Northern Front Range Air Quality Study will occur during 1997 and will be available in the future.  No special visibility studies have been conducted in the Northern Rocky Mountains or Northern Great Plains.

f.    Interpretation and Visibility Projections

Data from other IMPROVE visibility sites around the country have been presented graphically (Figures I-1 and I-2) so that visual air quality in the Central and Northern Rocky Mountains and Northern Great Plains regions can be understood in comparison with other U.S. regions.  Long-term trends fall into three categories: increases, decreases, and variable.  Using the visibility sites summarized for this report, the majority of data show no apparent temporal trend.  Long term increases or decreases in visibility conditions may have occurred over the past 10, 20 or 50 years, but the data are sparse and, therefore, may not provide for an accurate trend analysis.  Continued monitoring is necessary to identify local source impacts.  Additional data and in-depth modeling and analysis are required to evaluate regional trends and future projections of impact from existing and future sources.

One aspect of visibility impairment, the incidence of prescribed fires and wildfires, is likely to increase in the coming decades as a result of past fire suppression. "Emissions from fire may represent the single most important change in air quality in the next 50 years" (Grand Canyon Visibility Transport Commission, 1996). The effects of fire on visibility will likely vary from year to year, depending on the frequency and intensity of natural and/or prescribed fires in each region.

Other long-term future impacts may include: increased organics and elemental carbon concentrations due to increased gas and mineral developments in the Central and Northern Rocky Mountains regions, and higher concentrations of organics in the Central Rocky Mountains due to increased population growth along the Colorado Front Range.